BANDPASS FILTER DESIGN WITH SPURIOUS FREQUENCY REDUCTION CAPABILITY

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABREVIATION

PCMBPF	Parallel Coupled Microstrip Bandpass Filter
BPF	Bandpass Filter
PCML	Parallel Coupled Microstrip Line
CAD	Computer Aided Design
LAN	Local Area Network
FR4	Flame Retardant 4
W	Width
H	Height
S11	Return loss
S21	Insertion loss
ꞁ	Length
fc	Center frequency
s	Gap size
d	Thickness of the substrate
ε_r	Dielectric constant
Z_o	Input impedance

ABSTRACT

Passband microstrip coupled line filter are widely used in daily microwave engineering practice. There are various topologies to implement microstrip bandpass filters such as end-coupled, parallel coupled, hairpin, interdigital and combine filters. This thesis discusses design, simulation, fabrication and testing using microstrip technology. The choice of a parallel coupled filter topology is discussed and an application of the grooved substrate is presented to suppress the first spurious of Parallel Coupled Microstrip Bandpass Filter (PCMBF). Band pass filters (BPF) are significant role in wireless communication systems. These filters present an undesired pass band at twice the design central frequency of the filter. The narrowband with spurious suppression is achieved by using two stage PCMBF, BPF was designed by replacing the tight couplers are arranged at the input and output of the filter whist the weak couplers at the middle section of the tight coupler with optimize groove. By using Sonnet Lite software it shown the BPF with 2.99GHz cut off frequency and bandstop of to 7GHz has been simulated and fabricated on Flame Retardant 4 (FR4) substrate by using etching process. Significant spurious suppression up to 33.23dB is measured at 5.96GHz.

ABSTRAK

Mikrostrip penapis lulus jalur digunakan secara meluas dalam kejuruteraan gelombang mikro. Terdapat pelbagai topologi untuk melaksanakan mikrostrip penapis lulus jalur seperti *end-coupler, parallel coupled hairpin, interdigital* dan *combline.* Tesis ini membincangkan reka bentuk, simulasi, fabrikasi dan pengujian dengan menggunakan teknologi mikrostrip. Pemilihan topologi penapis selari dibincang dan penggunaan *substrate* beralur dibentangkan untuk mengurangkan *spurious* yang pertama dari *Parallel Coupled Microstrip Bandpass Filter (PCMBF). Band pass filters (BPF)* berperanan penting dalam sistem komunikasi tanpa wayar. Penapis ini direka supaya melepaskan frekuensi yang tidak dikehendaki ditapis difrekuensi tengah. Pengurangan *spurious* dicapai dengan menggunakan dua peringkat *PCMBF*, *BPF* direka dengan *tight coupler* di bahagian masukan dan keluaran, manakala pada bahagian tengah, menyusun penyusunan secara *weak coupler*. Dengan menggunakan perisian Sonnet Lite dengan alur optimum menunjukkan frekuensi tengah 2.99GHz dan *bandstop* sehingga 7GHz disimulasi dan fabrikasi pada *Flame Retardant 4* (FR4) *substrat*e dengan menggunakan proses *etching.* Penindasan *Spurious* ketara sehingga 33.23dB diukur pada 5.96GHz.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Filters are essential in the Radio Frequency (RF) front end of microwave wireless communication systems. Parallel coupled microstrip structure has been widely used as coupling components in the design of bandpass filter due to attractive features [2]. Filters are frequency selective networks designed so as to pass certain bands of frequencies and reject others. Filter are normally classified as low pass, band-pass, high-pass or band stop according to the bands it pass with low loss or in the case of the band stop filter, the band is reject. The four basic frequency responses shown in Figure.1.1, the lowpass filter, pass low frequencies from Direct Current (DC) up to the cut off frequency with no or little attenuation and attenuate high frequencies. The highpass frequencies pass above the cut off frequency and substantially reject below this frequency. The bandpass filters, pass one band frequencies and reject both higher and lower frequencies. The bandstop filters, eliminate or notch out specific frequency or band of frequencies from the frequency spectrum.

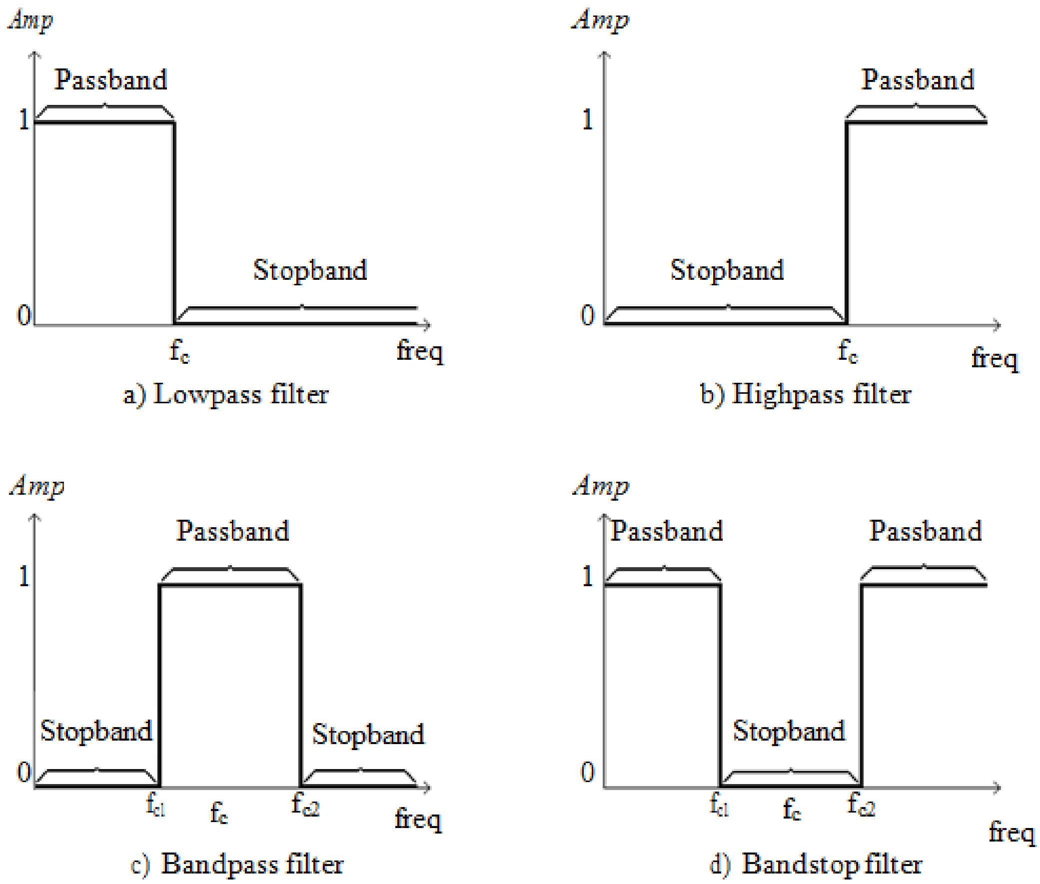

Figure 1. 1 : Filter types according to frequency selectivity.

The lowpass, bandpass and bandstop filters find important applications in signal selection in microwave systems and fabricated in microstrip. It is an important application and sometimes fabricated in microstrip in signal selection in microwave system. BPF is a passive component which is able to select signals inside a specific bandwidth at a certain center frequency and reject signals in another frequency region. Parallel-coupled microstrip bandpass filter is one of the most popular BPF and can be applied in many applications of microwave communication systems. General coupled bandpass filter is shown in Figure.1.2 illustrates a general structure of parallel coupled-line microstrip bandpass filter that uses half wavelength line resonators. This parallel arrangement gives relatively large coupling for agiven spacing between resonators, this filter structure is particularly convenient for constructing filter having wider bandwidth as compared to the other structures.

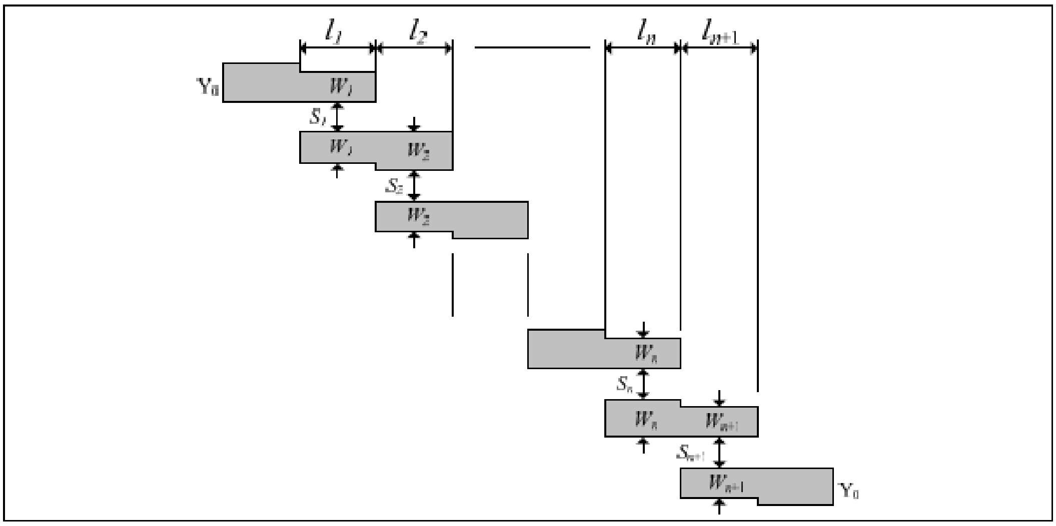

Figure 1. 2 : General structure of parallel coupled-line microstrip bandpass filter.

The filter structure is open circuited coupled microstrip lines. The components are positioned so that adjacent resonators are parallel to each other along half of their length. The resonators are coupled by means of gap capacitances between the resonator sections. The resonator lengths (l) and the couping gaps (s) between successive resonators are important design parameters [3].

This parallel arrangement gives relatively large coupling for a given spacing between resonators and making this filter structure particularly convenient for constructing filters having a wider bandwidth as compared to other type of bandpass filter.

1.2 Problem Statement

In microwave communication systems, the bandpass filter is an essential component which is usually used in both receiver and transmitters. Thus, the quality of bandpass filter is extremely important. Parallel coupled microstrip structure has been widely used as coupling components in the design of bandpass filter due to attractive. Although microstrip parallel coupled bandpass filter with uniform coupled microstrip line sections are popular, the conventional design suffer from the spurious passband at the harmonic response at second resonance frequency.

Detection of a wanted signal may be impossible if unwanted signals and noise are not removed sufficiently by filtering. Electronic filters allow some signals to pass, but stop others. To be more precise, filters allow some signals frequencies applied at their input terminal to pass through to their output terminals with little or no reduction in signal level. The spurious passbands especially appear at twice the centre frequency ($2f_o$). This spurious response degrades the rejection properties of the system.

The presence of harmonic at second resonance frequency also worsens the performance of upper stopbands and lead degradation of the overall systems performance. These effects are mainly due to the presence of even and odd mode at the parallel-coupled elements, with difference in their velocities. The various methods that have been proposed in the literature to suppress the filter spurious passband located at twice the centre frequency ($2f_o$). A new method proposed to suppress the spurious response using a grooved substrate. The 3^{rd} order of chebyshev response was chosen to investigate the performance of the filter, with and without periodical square grooves.

1.3 Objectives

The objectives of this project is,

i) To designed parallel coupled bandpass filter for 2.99GHz at S- band (2GHz to 4GHz) operating frequency.

ii) To analyse the performance of the designed filter in terms of frequency response, reduce at the first spurious passband.

iii) To compare between simulation result and measurement result by referring at frequency response.

1.4 Scopes

i) Design and analyse the results by using Sonnet Lite software, an analyse response referring in term of S-parameter insertion loss (S21) and return loss (S11).

ii) Analyse the result by comparing simulation and measurement for conventional and proposed filter design. The filter characteristic according a shape of groove with specified dimension will be proposed.

iii) The microstrip filter on the FR4 board was fabricate by using etching technique, to operate at S-band frequency (2GHz- 4GHz) useful in full-duplex local area network (LAN) communication.

CHAPTER 2

THEORETICAL BACKGROUND

2.1 Background

Parallel Coupled Microstrip Bandpass Filters (PCMBF) is widely employed in many microwave systems. Designs of PCMBF used the Parallel Coupled Microstrip Line (PCML) structure as the main coupling component [2]. The required design parameters of bandpass filter can be easily derived for Butterworth, Chebyshev or other prototype in many literatures [4]. A microstrip filter is a two port network used to control the frequency response at a certain point in a microwave system by providing transmission at frequencies within the passband of the filter and attenuation in the stopband of the filter [5]. Filters are frequency selective networks designed so as to pass certain bands of frequencies and reject others. Filter are normally classified as low-pass, band-pass, high-pass or band stop according to the bands it pass with low loss or in the case of the band stop filter, the band it reject. Low-pass, band-pass and band stop filters find important applications in signal selection in microwave systems. An example of response of ideal bandpass filter is shown in Figure. 2.1.

Today, most microwave filter design is done with sophisticated computer-aided design (CAD) packages based on the insertion loss method [2]. CAD packages are now available which enable direct determination of input impedance (Z_o) and other data for given substrate of width (w), height (h), thickness (t), dielectric constant (εr) and frequency input.

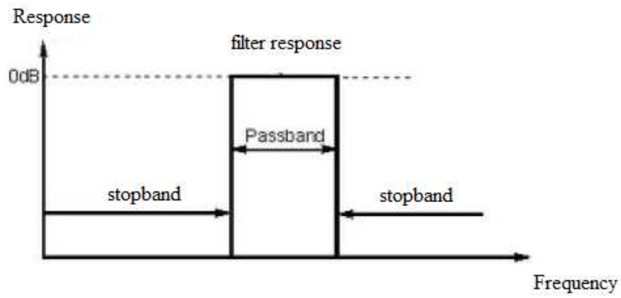

Figure 2. 1: Response of ideal bandpass filter.

Most RF/microwave filter and filter components can be represented with a two port network as shown in Figure. 2.2, where V_1, V_2 and I_1, I_2 are voltage and current variables at ports 1 and 2. The terminal impedances, Z_{01} and Z_{02} and E_s is the source.

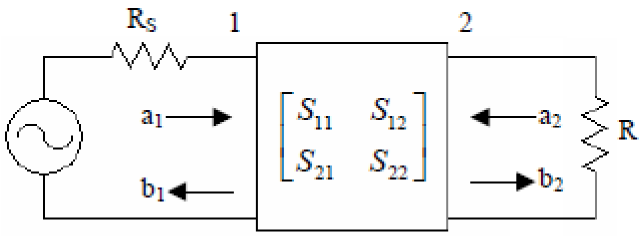

Figure 2. 2 : Filter as a two-port network with S-parameter representation.

The scattering or S parameters of a two port network are defined as;

$$S_{11} = \frac{b_1}{a_1}|a_{2=0} \qquad S_{12} = \frac{b_1}{a_2}|a_{1=0}$$

$$S_{21} = \frac{b_2}{a_1}|a_{2=0} \qquad S_{22} = \frac{b_2}{a_2}|a_{1=0} \qquad (2.1)$$

Where a_n= 0 no reflection from terminal impedance at port n, be written as:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} S_{12} \\ S_{21} S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \qquad (2.2)$$

The parameters S_{11} and S_{22} are reflection coefficients and S_{12} and S_{21} the transmission coefficients. The parameter directly measurable at microwave frequencies and an amplitudes are given in decibels (dB), are defined as ;

$$20\ log|S_{mn}|dB \quad m,n = 1{,}2 \qquad (2.3)$$

2.2 Planar Bandpass Filters

Bandpass filter is one of the most important filter in the communications systems, it can be classified by bandwidth to narrowband, wideband and ultra-wideband filter. The main challenging for designers is to design a bandpass filter with compact size, low lossless and wide stopband.

2.2.1 Microptrip line

Many electromagnetic circuits are implemented with the form of transmission line structures based on planar printed circuit boards (PCBs), which are composed of a dielectric material layer and ground/signal metal planes. One of the most widely used transmission lines for high frequency circuits in microstrip line. The microstrip are used for circuit components such as filters, coupler, resonator, antenna and so on. In comparison with the coaxial line, the microstrip line allows for greater flexibility and compactness of design [6]. A microstrip line consists of a dielectric substrate covered by metal layers on both sides, one for signal line and other one for the ground plane. The geometry of a microstrip line is shown in Figure. 2.2.

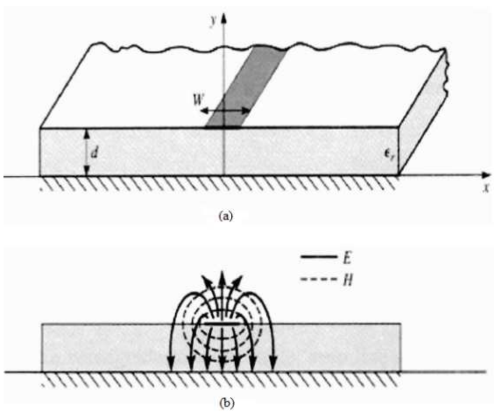

Figure 2. 3 : Microstrip Transmission Line. (a). Geometri (b). Electric and Magnetic Field Lines

Which,

W = is the width of printed thin conductor

d = is the thickness of the substrate

ε_r = is the dielectric of the substrate

The top conductor strip, the dielectric substrate and conductor ground plate form a microwave transmission line. The combine structure acts as s guide to the transmission of electromagnetic waves. Although it's open structure has some limitations it is an especially suitable medium for the connection of microwave integrated circuit devices. It is ideal for applications where low volume and weight are important and lends itself to methods of high volume and low cost production.

Microstrip is used over the frequency range from below 1GHz to 40GHz. Below 1GHz circuit dimensions become excessively large, above 40GHz circuit dimensions are very small and circuit lossless become high.

2.2.2 Overview of Microstrip

The microstrip structure does not have dielectric above the strip (as in stripline). So, microstrip has some usually most of the field lines in the dielectric region, concentrated between the strip conductor and the ground plane. Some of the function in the air region above substrate and the microstrip line cannot support a pure TEM wave. In most practical application, the electric substrate is electrically very thin ($d \ll \lambda$). The field are quasi TEM (the fields essentially same as those of the static case). Microstrip is by far the most popular microwave transmission line, especially for microwave integrated circuits and MMICs (Monolithic microwave Integrated circuits). The major advantage of microstrip over stripline is that all active components can be mounted on the top of the board. The disadvantages are that when high isolation is required such as in a filter or switch, come external shielding may have to be considered. Given the chance, microstrip circuits can be radiates, causing unintended circuit response. A minor issue with microstrip is that it is dispersive meaning that signals of different frequencies travel at slightly difference speeds [5].

2.2.3 Microstrip Substrates

The characteristic of some substrate materials are ideally a substrate should have very low-loss and constant dielectric properties over the range of frequencies for which it is used, excellent temperature and dimensional stability. It should be chemically resistant, be easy to machine and provide a good thermal expansion to the strip conductor material.

2.2.4 The advantages and disadvantages of Microstrip

The microstrip has their own advantages compare to other microwave transmission like waveguide, coaxial cable, strip line and etc.

The advantage of microstrip :

a) To make easier fabrication of complex circuit.
b) Smaller size and light.
c) Has a good reliability
d) Has a wide bandwidth
e) Good reproducibility

The disadvantages of microstrip :

a) Using the microstrip lines will be given high attenuation.
b) Using the microstrip will generate the low power.

CHAPTER 3

LITERATURE REVIEW

Coupled microstrip lines have been widely in design of bandpass filters in many microwave systems. Various methods have been reported the article "Spurious Response Suppression in Microstrip Parallel Coupled Bandpass Filter by Grooved Substrates" (Mahdi Moradian and Majid Tayarani, 2008) [6]. The articles present an application of the grooved substrate to suppress response of microstrip parallel coupled line filter. The proposed method, the grooves are cut along the outer edge of each coupled line of the conventional filter and the other to equalize the modal phase velocities. It is shown that the grooves equalize the even and odd mode phase velocities in microstrip coupled line and suppress the spurious response. The simulation result shows that the selected groove shapes also have a effect on the designed filter performance.

The article "Harmonic Suppressed Single Groove PCML Bandpass Filter", (Jayaseelan Marimuthu and Mazlina Esa, 2009) [7]. The article present the design of single groove parallel-coupled microstrip bandpass filter with improved passband and filter harmonic suppression. The undesired filter harmonic spurious response is suppressed through transmission zero frequency realignment method. The suppression of harmonic response carried out by transmission zero realignment method using a simple modification a single groove at the center PCML structure. A single groove is introduced at the center of PCML structure to control the transmission zero which depends on even and odd mode parameter. Figure. 3.1 shows the layout of a PCML structure of width (w), gap size (s) and length (l), with and without groove. H and W are the height and width of the single groove. For a given bandwidth, operating frequency and passband response, the w, s and l of each structure are calculated by using even mode impedance Z_{oe}, and electrical length θe, odd mode impedance Z_{oo}, and electrical length θ_o. The geometric parameters of a single groove in PCML *wg* for simultaneously tuning zeros at ~2.0 *fo* harmonic suppression for various PCML structures. The results of optimized single groove dimensions for various PCML structures with *w* = 1.0 mm and *s*= 0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm and 1.0 mm are given in Figure.3.2. When *s* increased, respective harmonic suppression groove of larger size is required. The odd mode propagation with increasing *s*, the coupling between the two strips decreases and the wave travels faster. The groove width increased to compensate or slow down its phase velocity.

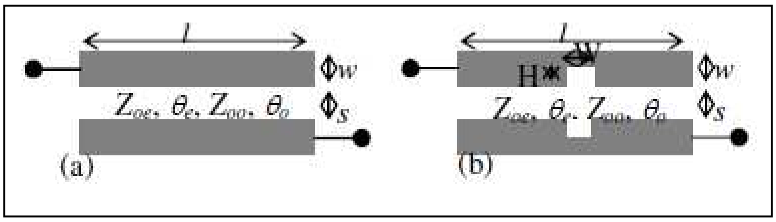

Figure.3. 1: PCML structure (a) Without Groove (b). With Groove **[7]**

Three-stage PCMBF designed with various combination of single-stage with optimized groove for harmonic suppression at different operating bandwidths. Figure.3.3 shows a three-stage PCMBF with optimized groove.

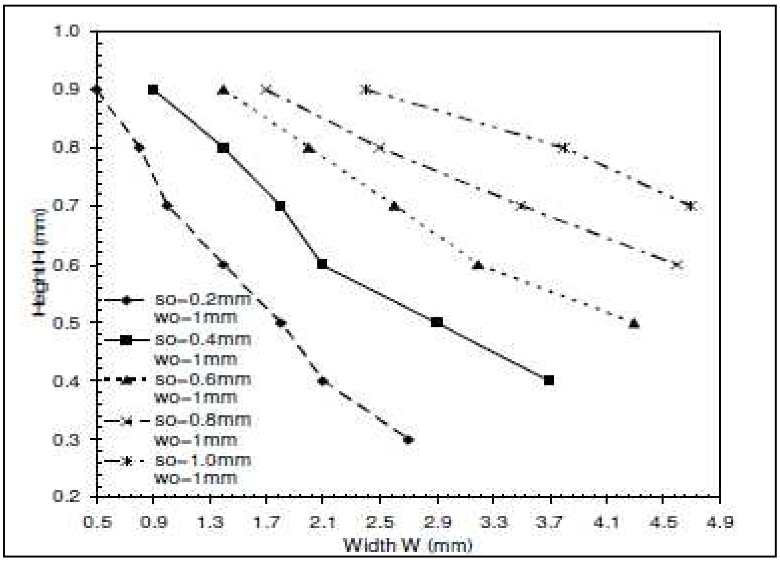

Figure.3. 2 : Geometry parameter for a optimized single groove with zeros simultaneously tuned at ~2.0f_o **[7]**

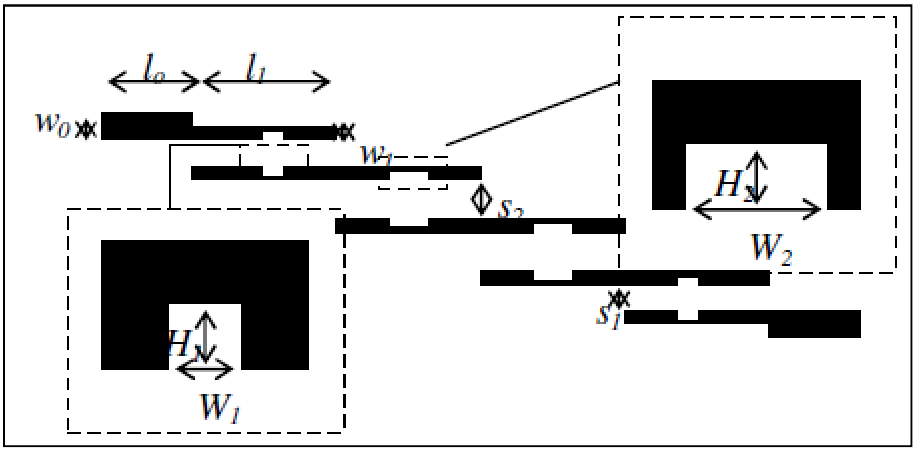

Figure.3.3 : Layout of Three Stage PCMBF with single Groove **[7]**

The other article is “An Implementation of Harmonic Suppression Microstrip Filter with Periodic Grooves” (Bong S.Kim, Jae W.Lee and Myung S.Song, 2004) [1]. In this paper, a new parallel-coupled-line microstrip band pass filter (BPF) improving the harmonic suppression performance of the second harmonic signal ($2f_0$, twice the passband frequency) is described. .It is found that the desired passband performance is improved and the harmonic passband signal is diminished by enforcing the consecutive patterns in coupled-line and increasing the number of grooves to the optimum values. The order-3 Butterworth BPF centered at 2.5 GHz with a 10% fractional bandwidth (FBW) and order-5 Chebyshev BPF centered at 10 GHz with a 15% FBW used. A filter and three square grooves are used, over 30-dB suppression at second harmonic signal achieved in simulation. The measured and simulated results in Figure.3.5 showing full suppression of harmonic response for various bandwidth in term of harmonic suppression.

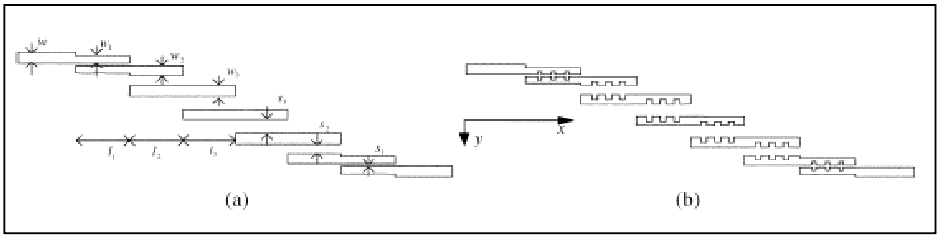

Figure.3.4 : Parallel coupled line Filter design (a). Conventional (b). Three square grooves **[1]**.

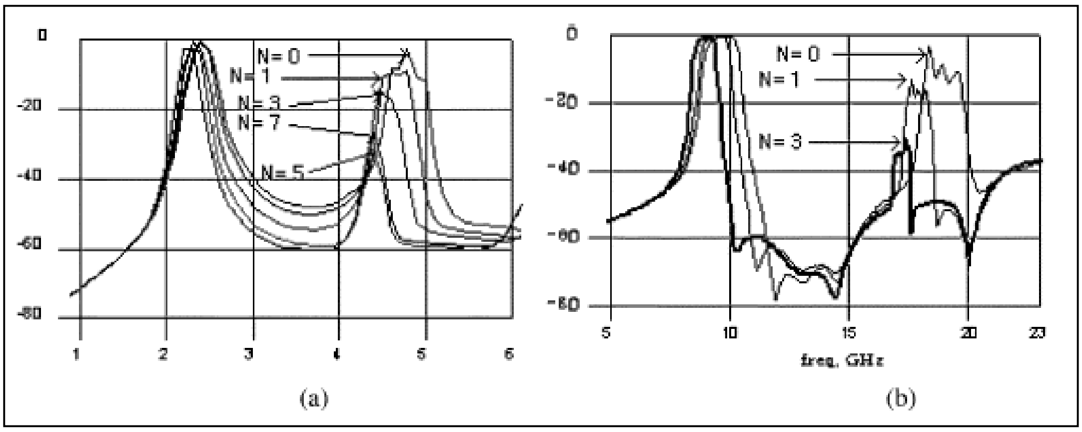

Figure.3.5 : Simulated result (a). Filter centered at 2.5GHz (b). Filter centered at 10GHz **[1]**.

The measurements realized with the Agilent E8357A PNA Series Network Analyser. Figure.3.6 shows the fabrication and simulation proposed filter results with the number of groove. The increases number of groove from 0 to 5, the second harmonic signal decreases with rejection level nearly -35dB, the number of grooves is 5 as shown in Figure.3.6 (d). The cut-off rate of the proposed filter for stopband was improved about 10 dB by comparing with that of the conventional coupled-line filter.

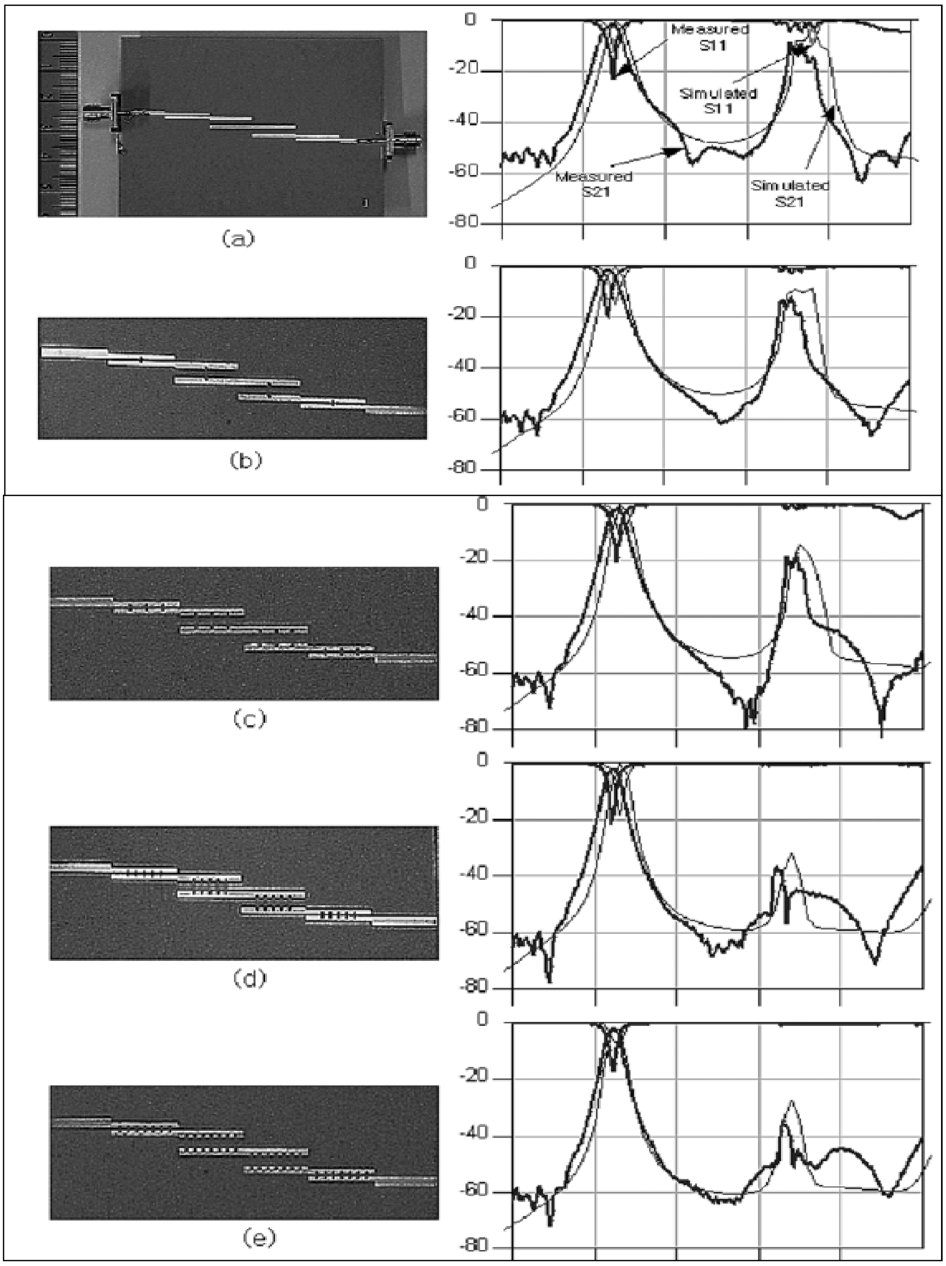

Figure.3.6 :Fabricated with groove number and S-Parameter response (a). 0, (b).2, (c).3 (d). 4, (e).7 **[1]**.

For a given PCML structure, the odd mode is propagating faster than the even mode, the electromagnetic energy for the odd mode concentrate around the center gap, while that for even mode is around the outer metallic edge [8]- [9] . Various techniques have been proposed to equalize the even and odd mode velocities or their electrical lengths to minimization of harmonic response. All the technique proposed, it does not require any restructuring or redesigning of PCMBF. It involves simple modification by introducing a single groove at centre of PCML.

Several techniques have been proposed to solve this problem [6]- [10]. In this project, bandpass filter design with spurious frequency reduction capability will proposed by a few couplers with various coupling coefficient based on the filter order. A two stage bandpass filter designed with tight coupler are arranged at the input and outputs. While the weak couplers at the middle section of the filter. Predicted frequency response is confirmed by a fabricate filter.

CHAPTER 4

METHODOLOGY

This chapter explains briefly about the process of designing and the software used to achieve in designing and the response desire. Before running the design, it is important to identify the flow of each process to ensure the performance of the filter design. For this project a bandpass filter is designed, then compared to the conventional and proposed. The studies were done by using microstrip line calculator to checked the filter design proposed. The overall design process was done by using Sonnet Lite software, fabricate and tested to analyse the performance of the filter. Figure.4.1 shows the overall design procedures of this bandpass filter.

4.1 Flowchart of Design Procedures

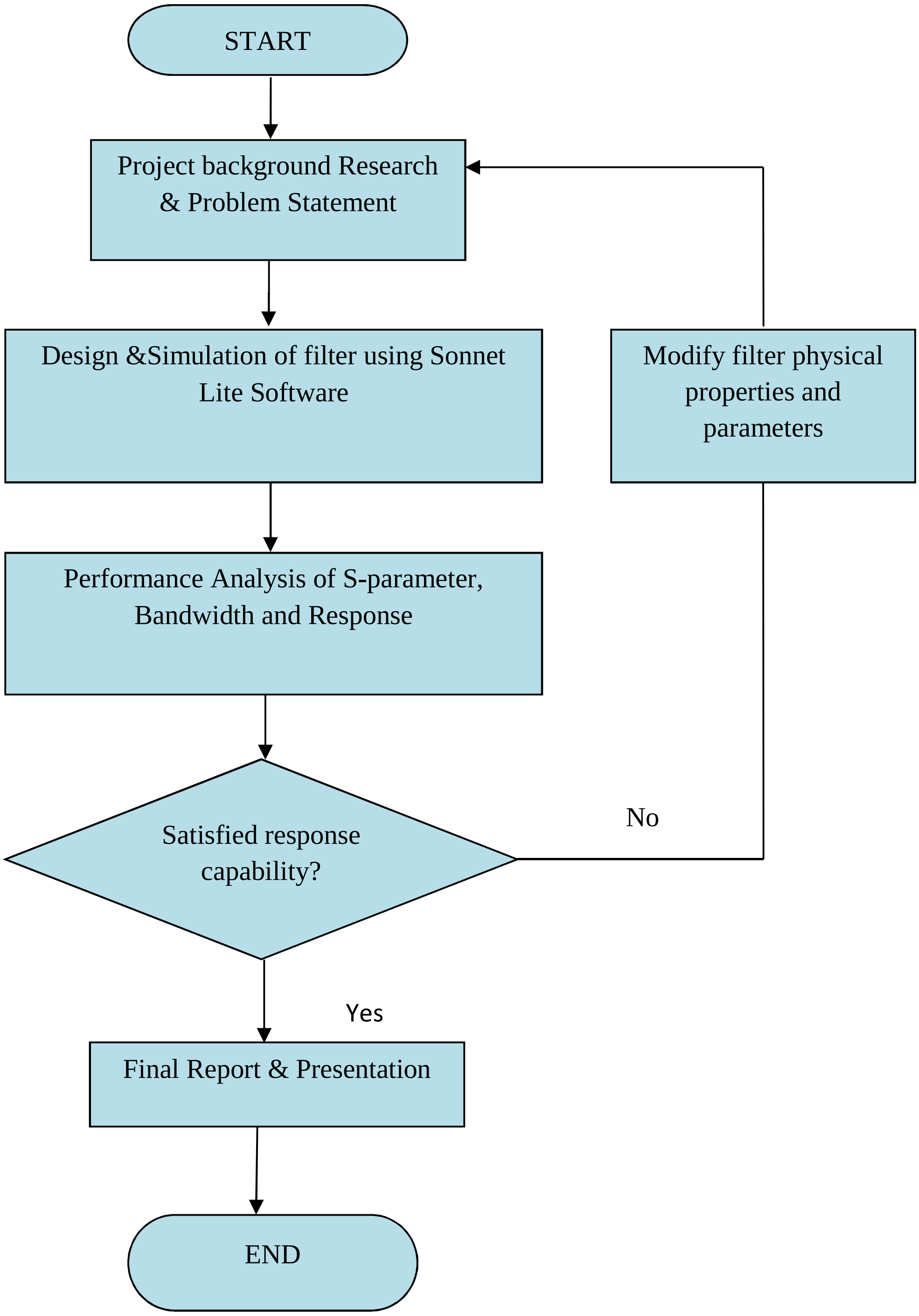

Figure 4. 1 : The flowchart of design procedure

4.2 Filter Design Method

A coupled line filter design with 0.5dB ripple, the center frequency 2.99Ghz, the input and output impedance are both 50Ω. The printed circuit board (PCB) material is FR4 with dielectric constant of 4.4 and the thickness is 1.27mm.

The first design steps are :

(i) The design procedure with a three pole (n=3) ladder type with element values are g_0=1.403, g_2=0.707 and g_3=1.984.

(ii) The design of microstrip band stop filter is to find an appropriate microstrip realization that approximates the lumped element filter. The filter is fabricated on a FR4 substrate having dielectric constant ε_r=4 and thickness h=1.27mm.

(iii) The design equations for parallel coupled bandpass filter given by [3].

$$\frac{J0,1}{Yo} = \sqrt{\frac{\pi}{2}}\left[\frac{BFW}{g_0 g_1}\right] \qquad (4.1)$$

$$\frac{J_{j,j+1}}{Y_0} = \frac{\pi FB}{2}\,\frac{1}{\sqrt{g_j g_j+1}} \qquad (4.2)$$

$$j = 1\ to\ n - 1$$

$$\frac{J_{n,n+1}}{Yo} = \sqrt{\frac{\pi FBW}{2 g_n g_{n+1}}} \qquad (4.3)$$

Where g_0,g_1 and g_3 are element of ladder with normalized cutoff frequency Ω_c =1 and FBW is the fractional bandwidth of bandpass filter. Jj,j+1 are the characteristic admittances of J inverter and Y_0 is the characteristic admittance of the terminating lines.

To realize the J-inverters obtained in above equations, the even and odd mode characteristic impedances of the coupled microstrip line resonators are determined by:

$$(Z0_e)j_{,j+1} = \frac{1}{Yo}\left[1 + \frac{J_{,j+1}}{Yo} + \left(\frac{Jj_{,j+1}}{Y0}\right)^2\right] \qquad (4.4)$$

$$(Z0_e)j_{,j+1} = \frac{1}{Yo}\left[1 - \frac{J_{,j+1}}{Yo} + \left(\frac{Jj_{,j+1}}{Y0}\right)^2\right] \qquad (4.5)$$

(iv) The next step of the filter design is to find the dimensions of coupled microstrip lines that exhibit the desired even and odd mode impendences.

Due to the complexity of calculating the coupling efficiency, CAD tools is used to find out the gap between coupling lines. The list below shows the results after the calculation :

$l_1 = l_3$ = 15.35mm

$w_1 = w_3$ = 1.95mm

$s_1 = s_3$ = 0.2mm

l_2=.15.35mm

w_2= 0.75mm

s_2= 0.5mm

Summarizing the above result after considering the specification of cell sizes, substrate, thickness and other related to filter design by using Sonnet Lite software, the final result becomes as follows;

L1,L3= 14.8mm, gap=0.2mm

L2= gap=0.5mm

Lo= 2.5mm x 11.6mm, for 50Ω

The entire filter is designed as Figure 4.2 and a three-dimensional view of the circuit in the six-sided metal box modelled view as shown in Figure 4.3.

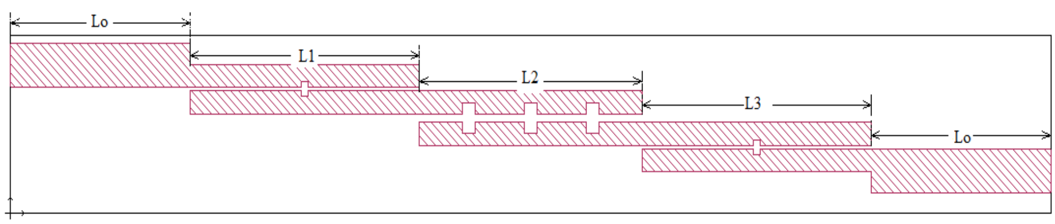

Figure 4. 2 : The filter design.

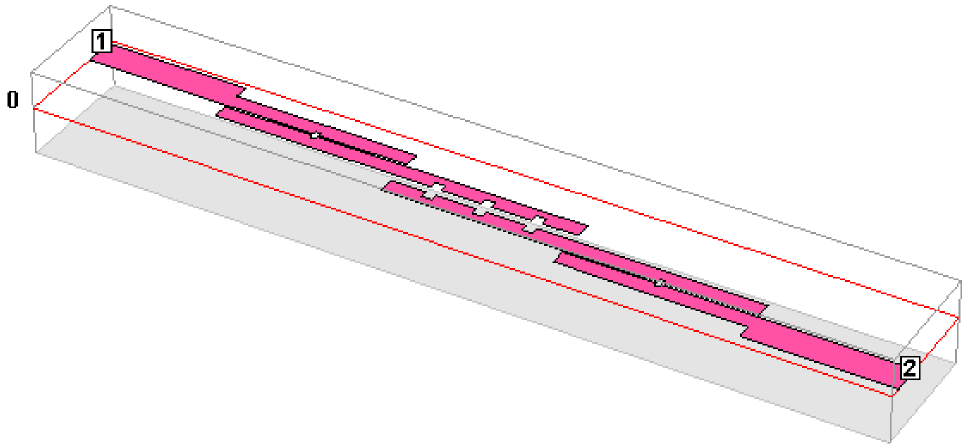

Figure 4. 3 : The three dimensional view of the circuit

4.3 The Sonnet Lite Software

The simulation tool is very useful and important for microwave circuit design. The design can simulate to check if the result meets design target and can do filter tuning and simulation again. By repeating filter tune and simulate step, the design is as close as possible to the design target. All the design and simulation were carried out using Sonnet [11]. The Sonnet Professional suite allows use of an unlimited memory space, limits to use of 32 Megabytes of memory for registered version and 1 Megabyte for unregistered versions. This provides high frequency 3D planar electromagnetic (EM) analysis. Figure 4.4 shows the icons are used for the Sonnet task bar.

The Quick Start Guide (QSG) appears to open the project editor or select Help Quick Start Guide from the project editor main menu. This guide provides step by step directions in how to create a circuit geometry in the project editor. The Quick Start Guide as an instructor to keeps track of which steps have been and use. The QSG mode has been selected. Clicking on the step itself displays a brief set of instructions for completing that particular step. After completed a step a green check mark appears next to the step. The steps do not need to be executed in order but if skip over a required step in creating project a red "x" appears next to the step as a reminder that the step has not been completed. The Help button at the bottom of the brief descript for detailed help on the step.

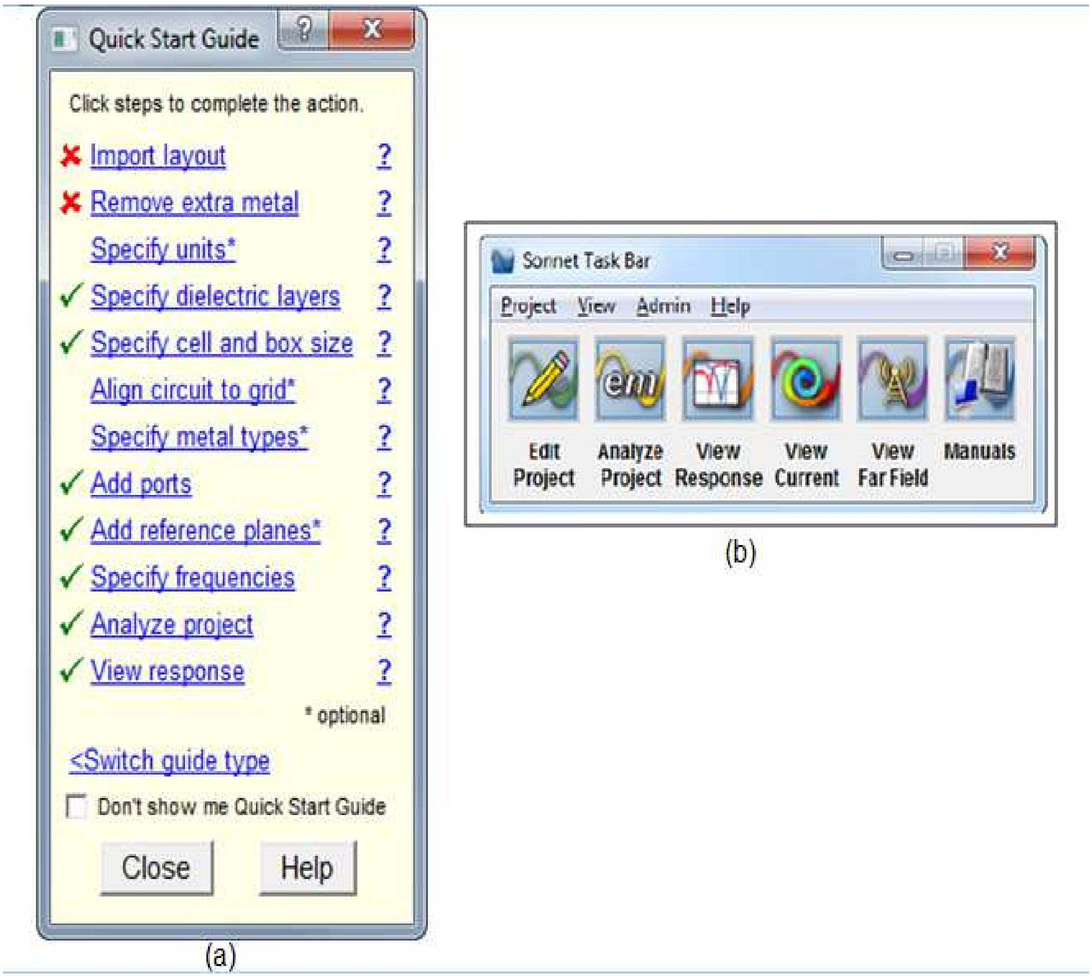

Figure 4. 4 : Sonnet Lite Software (a). QSG menu mode. (b). Front page menu.

All Sonnet geometry projects are composed of two or more dielectric layers, no limit to the number of dielectric layers in a Sonnet geometry project, but each layer must be composed of a single dielectric material. Metal polygons are placed at the interface between any two dielectrics. Figure.4.5 shows the task bar for setting the thickness of dielectric layer. The Dielectric Layers dialog box, allows specification of the dielectric layers in the box, the project editor “level” number appears on the left. A “level” is defined as the intersection of any two dielectric layers on circuit material placed.

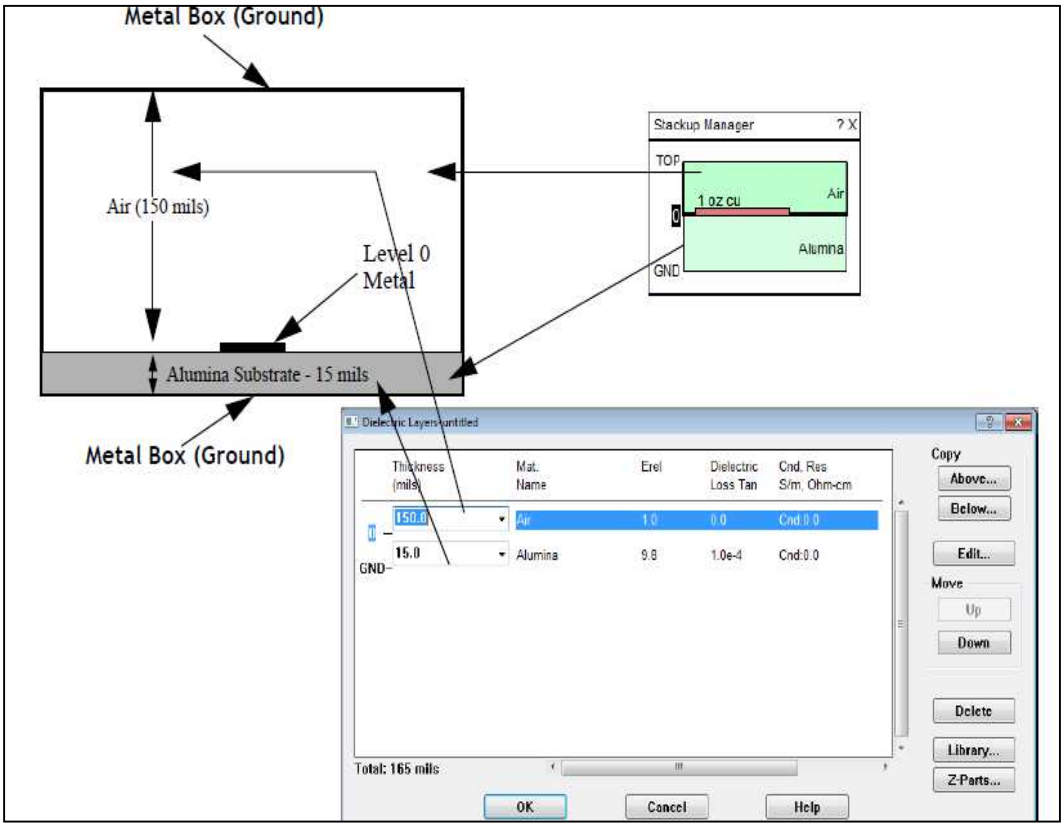

Figure 4. 5 : Task Bar Menu for setting value of Dielectric layer

There are two types of projects in Sonnet: the Geometry Project and the Netlist Project. In this project, the geometry project is used are shown below in Figure 4.6.

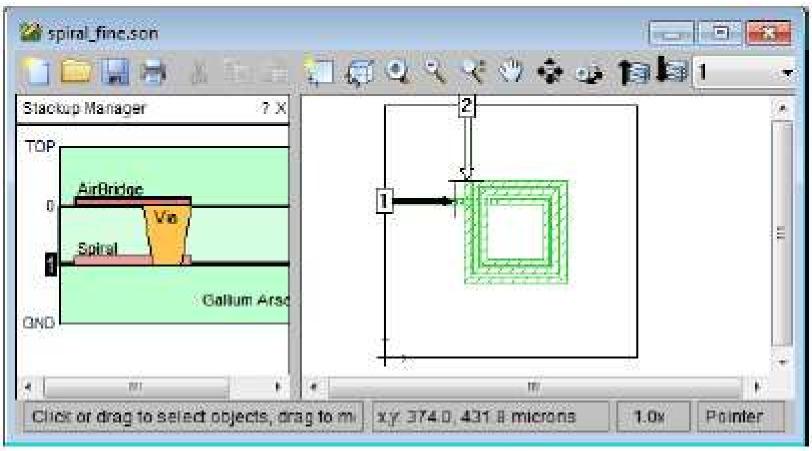

Figure 4. 6 : A Geometry Project.

4.3.1 Procedure of Sonnet software.

In this project, the geometry project is used. The overall design process is done by following step-by-step procedures using Sonnet Lite software. The step-by-step procedure is illustrated in the following figure.

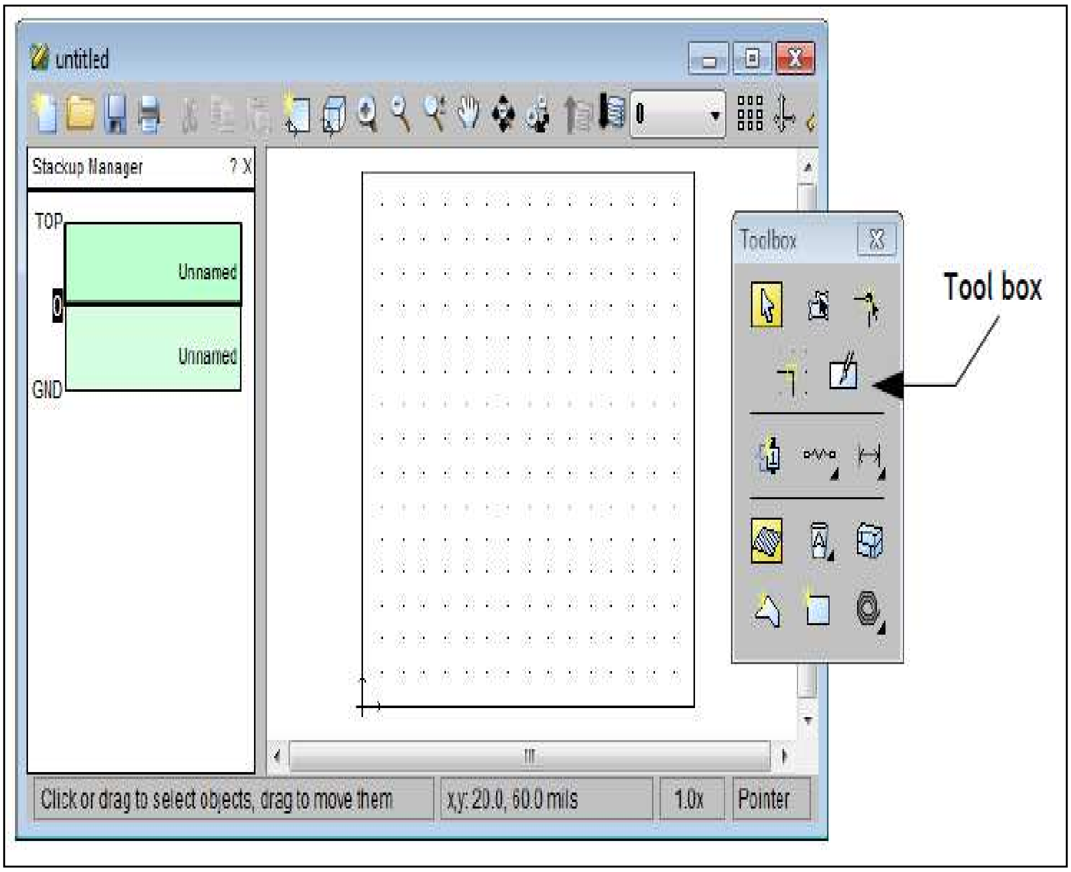

Figure 4. 7 : Sonnet Project Editor

Figure.4.7 shown a Sonnet project editor are using for make the geometry project. Firstly to create a new project, select **File** >> **New Geometry** from the Sonnet task bar. This command opens a new geometry file in the project editor. The window will have a blank substrate to indicate that no circuit geometry has been input yet.

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